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DEFORMATION AND RESPONSE OF CONTINUOUS AND RESTRAINED POST-TENSIONED CONCRETE SLABS AT HIGH TEMPERATURES

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Abstract. *The improvement of modelling capabilities that could enable defensible performance based structural fire design of post-tensioned (PT) concrete buildings requires detailed validation data from densely instrumented experiments that incorporate as many of the relevant structural properties of as-built construction as possible. Experiments are presented on three 3-span continuous, restrained PT concrete slab strips under sustained service loading and exposed to severe localised heating under constant incident heat flux. A similar yet highly complex deflection response to high temperature is presented for all three slabs. The possible physical mechanisms responsible for the observed complex high temperature deformation response are presented and discussed. The overarching objective is to help steer future research for the development of rational fire safety strategies for PT concrete (and reinforced concrete) buildings by interrogating these systems' real behaviour in realistic fire scenarios.*

1 INTRODUCTION AND MOTIVATION

Performance-based design is the growing paradigm in contemporary structural engineering, and structural fire safety engineering is no exception to this. Advocates of performance-based methodologies seek to adopt sophisticated fire strategies tailored to individual buildings and needs. In particular, these strategies are being applied to optimized reinforced concrete buildings, including those that apply steel prestressing tendons as post-tensioned (PT) reinforcement. However, the current understanding of prestressing steel behaviour at high temperature is based largely on outdated research that fails to properly account for material property changes at elevated temperatures. Furthermore, real fires in real PT concrete buildings have the potential to induce – indeed have induced in real fires – unique failure mechanisms that cannot be observed or accounted for using standard fire furnace tests [1]. Current modelling tools used to establish structural fire safety engineering strategies may thus lack realistic experimental validation and verification, leading to the development of potentially unconservative performance-based strategies for PT concrete buildings (indeed for all concrete buildings). To support the improvement of modelling capabilities that would enable credible performance based design of PT concrete buildings, there is a need for densely instrumented experiments that incorporate as many of the relevant structural properties (post-tensioning, continuity, restraint, realistic scale, unbonded reinforcement, etc) of as-built PT construction as possible; this need is partly addressed in the current paper by presenting experiments on three 3-span continuous, restrained PT concrete slabs (slab strips) under sustained service loading and exposed to severe localised heating using radiant heaters. While initial outcomes of these slab tests have been presented by Gales et al. 2013 [2], the unique deflection response that was observed has not previously been presented in detail. This paper addresses this shortcoming by providing an expanded discussion of the observed deformation response in an attempt to

steer future research towards improving capabilities in engineering rational performance based fire design of PT concrete buildings.

2 EXPERIMENTAL METHODOLOGY

The test program was designed to be the most simplistic slab that could still account for as many of the relevant structural properties of as-built PT concrete construction as possible. The resulting tests are the first to consider continuous, PT configurations at high temperature including axial, vertical and rotational restraint across multiple spans, whilst also accounting for bonded and unbonded PT construction. The testing configuration is illustrated in Figure 1. The slabs (denoted A, B, and C) were cast from concrete of grade C40/50 with 10 mm maximum size mixed gravel aggregate. Each slab was cast with a single embedded parabolic profile seven-wire steel prestressing tendon (Grade 1860, with a minimum prescribed concrete axis distance cover of 35 mm) and non-prestressed mild steel reinforcement (Grade 500, with an axis distance of 25 mm). Slabs A and C had unbonded PT tendons, whereas Slab B had a bonded PT tendon. It is important to note that the draped parabolic prestressing tendon profile resulted in an eccentric prestressing force at midspan.

2.1 Test procedure

The slabs were tested individually after curing for at least six months. The testing procedure for each slab is reviewed in this section; specific details being provided where the individual tests differed.

The testing procedure began by connecting the slabs to fixed steel supports connected to a structural strong floor, thus creating a frame of representative restraining stiffness of a real PT building. This supporting system resulted in the slabs being continuous over three spans with two small end cantilevers. The restraining frame was instrumented with strain gauges to allow indirect measurement of forces exerted on the supports during high temperature exposure. After the slabs were connected to the restraining frame their prestressing tendons were post-tensioned while monitoring structural response. The tendon in Slab B was grouted after post-tensioning to create a bonded PT condition, as already noted. To simulate a longer total unbonded tendon length, Slab C incorporated a disc spring anchorage at the dead end anchorage; this was specifically tuned to a specific stiffness so as to simulate an additional length of unbounded prestressing tendon.

After waiting for short-term prestressing losses and time for the grout hardening in Slab B, the slabs were loaded with lead bricks to give a sustained loading of approximately 2 kN/m of span length. These bricks were used since with small deflections they remain stationary and they can be directly exposed to temperatures below 300°C. Sustained loading during high temperature testing was approximately 40% of the calculated design ultimate capacity (with reduction factors taken as unity). After loading, the short-term behaviour of the slabs was monitored.

The slabs were then heated by locally exposing the central span only to heat from an array of propane-fired radiant heaters placed beneath the slabs. The thermal exposure was highly repeatable between tests [2]. Localised heating was chosen since it has been shown by the authors to be the most critical for stressed unbonded prestressing tendons, for which localized heating can rapidly lead to tendon rupture. This is due to complex interactions between stress relaxation (due to creep elongation and thermal expansion), strength and stiffness reductions at elevated temperatures (see [3] for discussion). Since Slab C incorporated a disc spring anchorage to simulate a longer total tendon length, this resulted in a smaller effective heated length ratio for this slab. Once the code-prescribed critical temperatures of the prestressing tendon were achieved, as indicated by monitoring temperatures in the concrete at the tendon axis distance depth, the radiant heaters were turned off and the cooling phase response was also monitored. The critical tendon temperature for slabs A and B was taken as 350°C (based on guidance from Eurocode [4]), whereas the critical temperature was assumed to be 427°C for Slab C (based on guidance from IBC guidance [5]).

2.2 Instrumentation

Deformations and temperatures were recorded at various locations during all stages of testing (including the post-tensioning and loading stages). All three slabs were densely instrumented to record temperatures, with 24 K-type thermocouples within the central span. Temperatures were also monitored outside the heated region. In the central span both unexposed and exposed surface temperatures were recorded, as well as temperatures at the prestressing and non-prestressed reinforcement axis distances. Three ‘spring-pot’ (SP) transducers were used to measure slab deflections at mid-span (one SP) and quarter-span (two SPs) for all tests. The unheated spans were also monitored for deflection at their mid spans. Two load cells were used to measure prestressing tendon stress levels at both end anchorages for all tests (including Slab B with a bonded tendon). A thermal camera was used to accurately characterize the exposed surface temperatures of the slab within the heated region. A high-resolution digital image correlation system was used to monitor deformations throughout the heating phases of the tests.

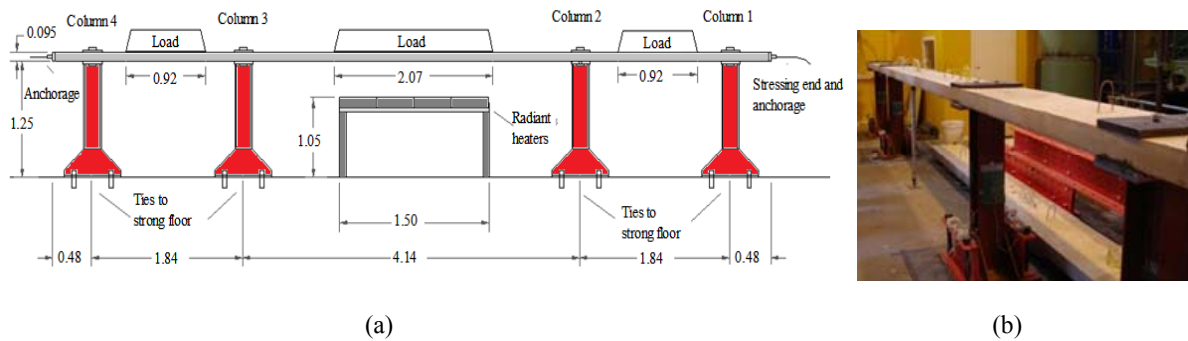


Figure 1. (a) Schematic showing the test set up and selected geometry (dimensions in m) and (b) a photo of Slab A after being attached to the restraining frame.

3 DEFLECTION RESPONSE DURING HEATING AND COOLING

All three tests showed a highly complex, similar, and in several respects, unexpected deflection response during high temperature exposure, despite the structural system’s relatively simple construction. For all stages of high temperature testing, a generalised summary of the measured deflections for the Slab A is noted numerically in Figure 2 (with the deflection profile artificially amplified for clarity and shown relative to deflections at the onset of heating). The figure shows several phases of slab deformation that occurred during testing (phases denoted 1-3 in heating and 4-5 in cooling). All slabs exhibited a similar response to heating and cooling. Figure 2, shows that deflection values were generally small (peaking at approximately 10 mm or span/400). In addition, testing also revealed that with localised heating, the slabs did not follow a typical gravity deflection profile for the central span. Rather deflection was primarily influenced by thermal bowing brought on from differential thermal gradients in the through-thickness.

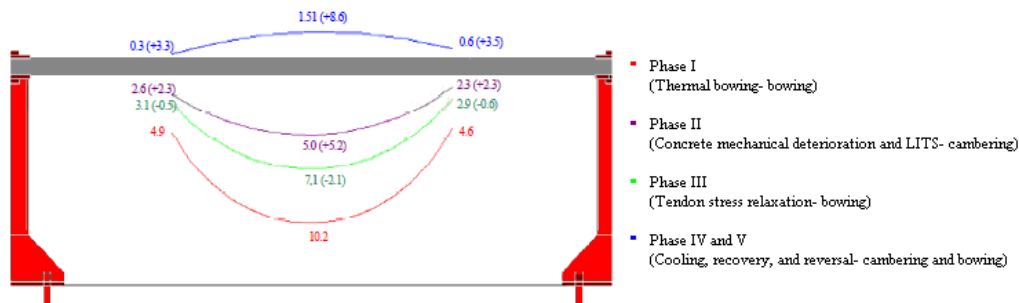


Figure 2. Slab A deflections at various phases of the test (values in mm, refer to Figure 3)

Figures 3-5 summarise the slabs' thermal and structural responses with time during both heating and cooling (measurements taken at mid-span). For rapid comparison, these figures present the mid-span vertical deflection relative to start time of heating, maximum thermal gradient (i.e. difference in temperature between the heated face and the cool face), exposed soffit surface temperature, and prestressing tendon (axis distance) temperature with time from the onset of heating. The average lateral restraining force developed on the 4 columns (measured by instrumenting and calibrating the vertical cantilever column supports with electrical resistance strain gauges) as well as the prestressing tendon stress level measured at the end anchorages for all tests are also shown. While such a complex and interesting deflection response has not been previously observed in traditional 'pass-fail' testing of simply supported elements tested in furnaces, they have considerable importance for demonstrating a credible ability to model real PT concrete structures when exposed to fire; a discussion of, and possible explanations for, the observed physical mechanisms that might be responsible are therefore given in this section.

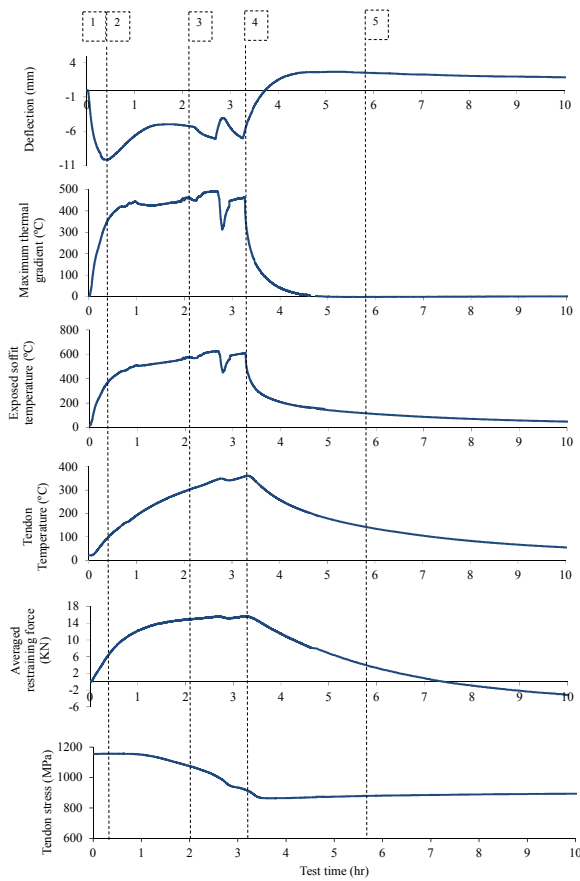


Figure 3. Slab A behavioural response (unbonded)

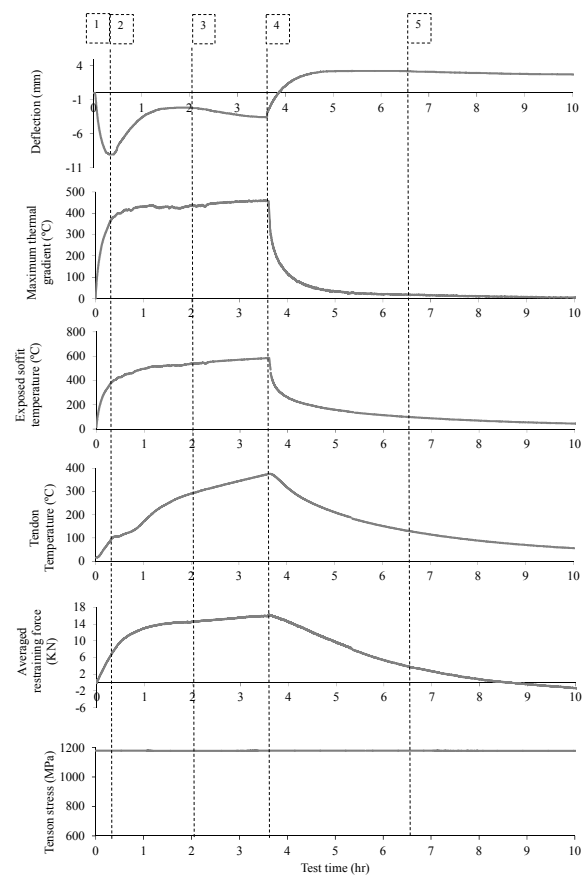


Figure 4. Slab B behavioural response (bonded)

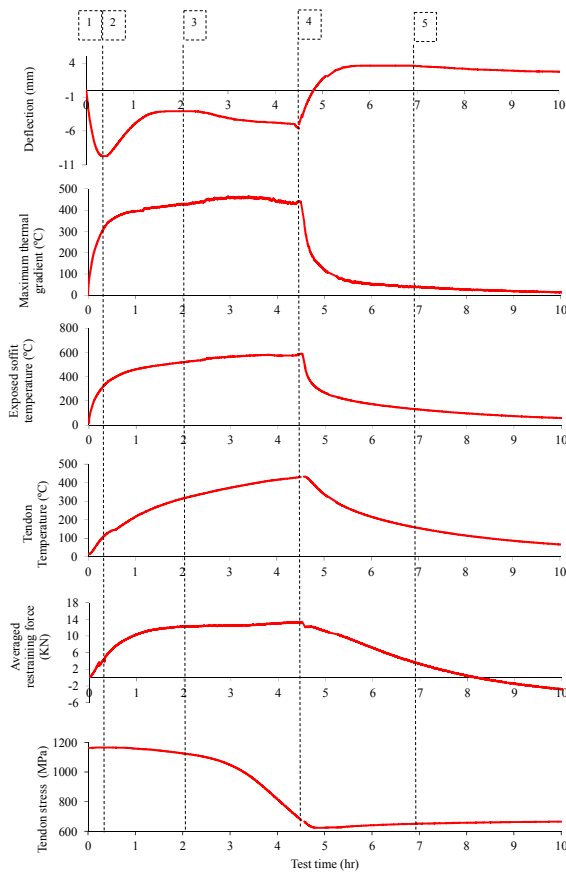


Figure 5. Slab C behavioural response (unbonded)

3.1 Phase I – Thermal Bowing

The similarities in response are striking, despite the differences in prestress characteristics for the three slabs. In all tests, rapid downward deflection was observed initially. Nearly 10 mm of initial downward deflection was observed in the first 30 minutes of heating in all tests.

This behaviour is easily explained. Figures 3 - 5 show that this phase of deflection is likely dependent on thermal bowing of the concrete. This is influenced by increasing thermal gradients with time ($>350^{\circ}\text{C}$) and the resulting differential thermal expansion of the concrete through its thickness. The resulting restraining forces measured during this phase also increase with the development of the thermal gradient. Since prestressing tendon temperatures were observed to peak around 100°C during this phase in all slab tests, little stress relaxation is expected. Indeed, a small *increase* in tendon stress (approximately 10 MPa in both unbounded slabs A and C) due to mechanical re-stressing of the prestressing tendons in Slabs A and C from bowing and slab elongation would be expected and is observed.

This phase ends when deflection reverses and the slabs begin to deflect upwards.

3.2 Phase II – Concrete Mechanical Deterioration and LITS

The second phase, showing upward deflection of the slab (i.e. a cambering of 5 - 7 mm in all tests), is less easily explained. Figures 3-5 indicate that cambering is observed despite an increasing thermal gradient for the full duration this phase. The gradient reaches $420\text{--}435^{\circ}\text{C}$ by the end of the phase and would lead to an expectation of additional thermal bowing and downward deflection in the absence of any prestressing force. An increase in restraining force also continues to closely follow the trends of an observed temperature gradient increase; however the slabs do not continue to deflect downward. It is clear that multiple, interrelated thermal and physical mechanisms must be occurring to cause this response.

This cambering response may be influenced by loss of stiffness of the heated concrete near the heated face. The exposed surface of the concrete in all cases in this phase ranges from 400 to 550°C . Concrete is known to suffer substantial stiffness losses at these temperatures. This stiffness loss supports an upward movement of the effective neutral axis of bending due to the eccentric prestress changes within the heated region. With the loss of stiffness and the maintenance of high prestressing levels in the tendon (measured prestress relaxation was at most 10% by the end of this phase for slabs A and C) it would be expected that the slabs would camber during this phase in testing. Under high initial compressive forces induced on the slab from post-tensioning, the upward movement of the slab can also be influenced by the occurrence of load-induced thermal straining (LITS) of the concrete within the heated region (see [6] for further discussion of LITS). The deflection response is further complicated by a possible (however minor in this case) shift in tendon eccentricity due to the melting of the polypropylene extrusion sheath (slabs A and C) or plastic corrugated duct (Slab B). This may occur for tendon axis distance temperatures exceeding 100°C and would decrease the tendon eccentricity by at most 2 mm. This eccentricity change

would have had a very small contribution to actually increase downward deflection (rather than cause camber). Phase II was considered to have ended when slab cambering transitioned once again into a downward deflection trend.

3.3 Phase III – Tendon Stress Relaxation

Cambering ceased in Phase II, followed once again by downward deflections when the prestressing tendon temperatures neared 300°C, as is indicated in Figures 3-5. This deflection was small at approximately 2 mm for all slabs.

In Phase III, the deflection trend resembles the beginnings of a traditional creep curve for a steel prestressing tendon [3]; this appears as the result of the known tendon stress relaxation at higher tendon temperatures, due to thermal relaxation and creep elongation and causing an effective loss of pre-compression of the slab. Gales et al. 2012 [3] have previously identified that most modern prestressing tendons show rapidly accelerating creep at temperatures above 300°C. The resulting reductions in tendon stress can cause global increases in deflection for the PT slabs, thus cancelling out the cambering effects of the locally heated region that occurred in Phase II. During Phase III, the thermal gradient is still observed however it is almost stationary and the rate of this increase is diminished significantly; subsequently additional deflection anticipated from thermal bowing is considered to be small. In Slab B there is a possibility that the bond between the tendon and grout had deteriorated effectively making a section of the PT reinforcement unbonded. This effect would create localised tendon stress relaxation zones within the slab. A post-test slab evaluation of the Slab B identified a region of slough off cover spalling, within this region significant cracking in the post tensioning grout was confirmed. This indicates that the bond may be compromised and localized relaxation of the tendon permitted.

Interestingly, in the test on Slab A, the radiant heaters failed briefly due to ‘blowback’ during Phase III. Figure 3 shows the sudden deflection response of the slab in cooling, immediately and profoundly effecting nearly all measurements and clearly demonstrating the importance of differential thermal gradients on concrete structures (i.e. as for steel structures, thermal deflections are far more significant than mechanical ‘load induced’ deflections). When the heaters failed, cooling of the slab began and cambering the slab resulted due to a decrease of the thermal gradient. The heaters were then re-ignited, and the slab, again under increasing thermal gradient, began to deflect again and resumed its similar response.

None of the slabs were taken to ‘failure’ (i.e. structural collapse). Heating was terminated once the prestressing steel tendons reached temperatures considered to be ‘critical’ (350°C as in Europe [4] for slabs A and B, and 427°C as in USA [5] for Slab C).

3.4 Phases IV and V – Cooling, Recovery, and Reversal

Upon halting the heat exposure the cooling phase was monitored for several hours (during phases IV and V). During these stages all slabs reversed their deflections by cambering approximately 7 – 9 mm after cooling.

Phase IV appears to be controlled by thermal contraction due to reductions of thermal gradient. This behaviour was briefly observed for Slab A in Phase III during ‘accidental’ cooling as noted above. During the initial portions of Phase IV, the prestressing steel tendon continued to relax in prestress, despite the overall cooling of the slab. This may be influenced by accelerating creep damage of the prestressing tendon as its temperatures still exceeded 300°C, and to the ‘thermal wave’ which will continue in the concrete even after the heating is removed. Once the prestressing tendon temperature dropped below 300 °C this prestress loss stopped and subsequently the tendon began to regain (recover) prestress as a result of thermal contraction of the steel on cooling. This would have also influenced the slabs’ deflections. However, rather than arch the slab up in camber due to tendon stress increase, the slab once again begins to show a new deflection phase. Phase V could be considered to occur when the exposed soffit of the slabs began to near 100°C in cooling. The slabs all began to deflect down slightly at this stage of testing. This deflection behaviour could be explained by the slabs’ absorbing moisture from

the atmosphere and thereby rehydrating the lime in the Portland cement. This action (however minor) could cause an expansive effect on the slab and act to deflect the slab downward.

Interestingly all slabs exhibited a relative camber after cooling (i.e. after cooling the residual deflection of all slabs was *up* relative their pre-heating condition). All slabs indicated a gradual decrease in the relative restraining force exerted on the columns, settling on a relative residual ‘pull-in’ restraining force on all supporting columns. All slabs also had less recovery of deflection when compared to the thermal bowing observed in Phase I. These behaviours are indicative of permanent plastic deformation of the structural system (both concrete and steel prestressing) and could potentially have significant consequences on a post-fire assessment of structural stability in real buildings (i.e. assessment of UPT buildings cannot necessarily rely on vertical slab deflection to provide an indication of structural damage due to heating). Slabs A and C exhibited more deflection as compared with Slab B, this likely due to prestress relaxation in the unbounded tendons for these two slabs. The bonded slab (Slab B) presumably maintained a greater proportion of its initial prestress and thus experienced the least overall deflection throughout testing.

3.5 Summary

For every fire and every PT structural configuration that might exist in a real UPT building the aforementioned five phase deflection response clearly cannot be assumed to be observed in all cases. As suggested by the discussion above, the deformation response of the slabs is controlled by a number of test variables and thermal/physical mechanisms. For instance, the severity and uniformity of heating induced on the slabs will play a highly significant role on the degradation of concrete properties and the in-service stress level of the post-tensioning steel. Different structural dimensions, PT tendon drape, loading level, restraining frame stiffness, and two-way reinforcement and prestressing (membrane actions) would all influence the observed response in a real building; in ways which are not yet understood. A different deflection response should be expected if experimental procedures are even slightly varied. The purpose of the current paper is simply to demonstrate the complexity of response, as a warning to those who claim that the response of UPT structures in fire is credibly understood; they are not. In the absence of additional testing, modelling may shed light on the response of these structures in different structural configurations. This assumes that modelling can demonstrate an ability to account for the complexities observed in the tests presented herein.

4 STEERING FUTURE RESEARCH

The tests presented herein provide real data for the development and validation of computational tools to enable analysis of full structural response of PT buildings in real fires. The slabs were not designed to provide ‘pass-fail’ fire test criteria for prescriptive design; such tests cannot account for the complexities of as-built construction. The tests represent the most simplistic experimental design possible which account for as many relevant as-built construction features as possible. The validation of modelling capability based on these (and other) tests will hopefully eventually enable designers to develop rational fire safety strategies for PT concrete buildings (or other optimized concrete building types). However, several areas require additional research attention to correctly account for the complexities in deformation observed in these tests; these are:

- **Mechanical re-stressing of unbonded tendons** – When exposed to heating, many inter-related structural mechanisms may influence the stress level of unbonded prestressing tendons. Additional research should attempt to consider the roles of thermal bowing, loss of pre-compression, and restraint on the stress level of unbonded tendons.
- **High temperature relaxation of prestressing tendons** – Deformation was shown to be heavily dependent on tendon stress relaxation due to thermal relaxation and creep elongation (particularly in Phase III). Although efforts have been made by the authors in the past to describe this behaviour with simplified modelling [3], an increasing error with the rate of heating can be identified in that work.

Future work must be done to define a tendon stress relaxation model that can correctly account for variable heating rates.

- **Consequences of tendon rupture** – None of the tests were able to examine the effect of prestressing steel rupture on load carrying capacity of UPT slabs. Research is needed to understand the effects of immediate load shedding to bonded (non-prestressed) steel reinforcement and whether the structure can maintain the applied load after tendon rupture.
- **Concrete behaviour in fire** – A detailed study into the thermal and mechanical behaviour of concrete and concrete structures may aid modelling efforts in the future to evaluate the responses observed during these tests. In addition, spalling; cracking; LITS; stiffness loss; material parameters in cooling etc. all need research to give confidence in modelling concrete behaviour. This is crucial to fully evaluate the behaviours observed; particularly the deformation shown in Phase II in all tests.
- **Accurate model inputs** – Any high temperature model must adequately account for the initial conditions of the structural system. For example the degree of pre-compression, forces exerted on the columns from post-tensioning etc. will aid in determining the degree of flexural/compressive prestress in the concrete at the start of heating, thereby allowing appropriate consideration of load-induced temperature effects.

5 CONCLUSIONS

The continuous, restrained, one-way spanning PT slabs tested herein exhibited five distinct phases of deflection under severe, localised heating and cooling. These trends appear to be influenced by a complex interplay between stiffness degradation of concrete, prestressing steel tendon plastic deformation, and differential thermal expansion/contraction. Attempts to numerically model these simplistic structural systems in fire must defensibly account for these (and other) complexities to be considered entirely credible; research needs have been identified to progress towards this objective. This will lead eventually to the development of rational fire safety strategies for optimised PT concrete buildings in real fires.

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